NASA Living With a Star

Science Architecture Team

Workshop: January 31, 2001
SAT Meeting: February 1-2, 2001
Greenbelt Marriott, Greenbelt MD

SAT Notes

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INTRODUCTION

This document records notes of the Living With a Star Science Architecture Team (SAT) workshop held on January 31, 2001, and followed by the SAT meeting of February 1-2, 2001, both held at the Greenbelt Marriott, Greenbelt Maryland. A list of scientific community invitees is given in Appendix 1. This group met with the members of the Science Architecture Team, and LWS scientists from NASA Headquarters, Goddard Space Flight Center, and the Johns Hopkins University Applied Physics Laboratory to survey science needs, and measurement requirements for the LWS program. A complete list of registrants is given in Appendix 2.

The purpose of the workshop was to gather together a group of experts sufficiently broad to address key questions relevant to LWS goals. Key science questions addressed included, for example, what determines when an SPE, geomagnetic storm, substorm, or ionospheric scintillations occur? what is their spatial and temporal development? what are mitigation strategies? Answers to questions such as these will make it possible to frame mission definition issues in the LWS program, for example, what are the required predictive capabilities? what parameters should be monitored, and where? what models are needed? In the area of the Sun-Earth climate connection, inquiry focused on mechanisms for variability to affect climate and weather. After an initial general session, the workshop broke into subgroups that addressed different aspects of the program.

The collected notes from these meetings form the contents of this document. Subgroup leaders and other contributors to the report were:

- Working Group 1 - Space Explosions (short time scales): Gary Heckman
- Working Group 2 - Space Storms (medium time scales): Karel Schrijver and George Paulikas
- Working Group 3 - Space Environment (long time scales): Rod Heelis and Judith Lean; Bob Robinson contributed the summary of observations needed as determined from Working Group 3.

Several recent reports have summarized science and certain operational issues in the general area of space weather. Most notable are:

- The National Space Weather Program, Implementation Plan, 2nd Edition, July 2000
- NASA Workshop on Sun-Climate Connections, Summary Report, March 6-8, 200, Tucson Arizona
(available at: http://www.ispe.arizona.edu/research/sunclimate/)
- The Space Weather Architecture Study, National Security Space Architect, 2000

The present set of notes is not intended to supplant these studies, but rather is intended to serve as a working set of notes for the Science Architecture Team that relate specifically to the Living With a Star mission. Thus, important scientific questions may fall outside the purview of this report, and the LWS program itself. In general, the current community priorities on science questions are contained in the recent Strategic Plan of the NASA Sun-Earth Connections program, with implementation intended to be carried out through the NASA Solar-Terrestrial Probes, Explorer, and Discovery programs.

...Glenn Mason, for the SAT

REPORT OF WORKING GROUP 1 (WG1) -- Space Explosions (Short Time Scales)

Living with a Star
Workshop of January 31, 2001
Working Group One (WG1)
Space Explosions (Short Time Scales)

(With additional magnetosphere-ionosphere-neutral atmosphere discussion)
Discussion notes including contributions to science questions, models and observations

Working Group One was tasked with covering the events that occur on time scales of hours. In keeping with the Living with a Star (LWS) objective, the discussions were aimed at science questions based on goals of understanding the physics of Sun-Earth connections leading to an ability to specify and predict societal impacts that result. The intent of LWS is to view the Sun-Earth connections from a system perspective that imposes the requirement that the science questions be considered in terms of a connected chain of phenomena from the development and release of activity at the sun to its propagation through the inner heliosphere to the point of affecting the environment at Earth. For Working Group One this understanding is intended to lead to the ability to make predictions of space environmental impacts at or near Earth with a few hours lead-time. The following requirements were included in the WG1 discussion.

LIVING WITH A STAR – A PERSPECTIVE ON NEEDS
Extracts relevant to explosive events (short time scales)
(from Withbroe, Workshop Notes)

- Prediction of Solar Proton Events (Astronaut safety, especially for deep space)
  - Need:
    - -Reliable warnings (minimize false alarm rate),
    - -Forecast of "all clear" for EVA's, being away from "radiation storm cellar" in deep space (e.g. when doing surface excursions)
  - Note:
    - -Can shield for SPE (via radiation storm cellar).
    - -GCR difficult to shield (higher energy)
    - -Goal is to minimize total exposure to radiation
- Prediction of geomagnetic storms for areas where effective mitigation is possible (e.g. power grid)
  - Need:

-Reliable forecasts (storm is coming) and very reliable shorter term (≥hour) warnings to minimize taking unnecessary mitigation by reducing capacity, etc. which cost $)

- Predictions of space environment for operation and utilization of space systems.

  Need: - To reliably forecast availability / accuracy / sensitivity of (TBD)
  communication and navigation systems affected by space weather (e.g. ionospheric scintillations).
  -To have more operators on call or to avoid uploads of software / critical commands during times of extreme space weather / SEU probability, etc.

The last section--predictions of effects on communication and navigation systems--was a joint concern with Working Group Two and in the afternoon of the workshop the discussions of these issues were split between the two groups.

A goal of the workshop was to insure that critical science issues have not been overlooked in the LWS science definition effort. But later in the process it will be necessary to prioritize the science to meet the LWS goals. The WG1 discussion spent some time discussing ways to organize the collected information to facilitate the prioritization process. A first approach, used in part of the discussions, classified the science questions as to whether they provided information about:

- **When is an event going to occur?**
- **Why does it happen or what will be its consequences? (how big and how fast?)**
- **How long will it last?**

The discussions about solar initiation of explosive events and the transit of coronal mass ejections and solar flares or their effects, solar energetic particles, and geomagnetic storms were accumulated by this organizational theme. A subsequent proposal out of the workshop is that the models necessary to construct the Sun-Earth causal chain be used as criteria for selecting science problems based on their contribution to the modeling process. A first-level set of models might include these. In other applications such as weather modeling, there may be an ensemble of models where more than one model is used at any link in the process. Four-dimensional data assimilation to integrate various model output and intermediate observations becomes a key aspect of such an effort. These same alternatives may apply to LWS.

Linked specification and forecast models with data assimilation at each stage
Solar Activity Development
Release of solar activity into the heliosphere—e.g. dynamic coronal models
Transport, modulation, development, and interaction of transient events in the inner heliosphere out to one AU.
The evolution of the more-slowly varying solar wind structure
Interaction of the solar wind with the magnetosphere
Linked magnetosphere-ionosphere-thermosphere models

A comment voice by participants after the workshop is concern that the observations made in LWS should be treated as a whole system also. These researchers emphasized that many will use data from several of the satellites and from auxiliary ground-based observations. They expect to run models or test data that propagate physical phenomena from one part of the Sun-Earth environment to another. Consistency and uniformity in data structures and formats will facilitate this. It is important, according to these comments, that data from the various sources lend themselves to easy integration into the models. Further, they spoke of having the models in a consistent environment so that new algorithms can be tested as modules within the total system context.

Science questions as collected in discussion
FLARES/CORONAL MASS EJECTIONS (CMEs)
(1) When is an eruption/event going to happen?

- Why are there active longitudes?
- Are there observable precursors to the emergence of active regions, especially magnetically complex ones?
- What determines whether a magnetically complex active region, such as a delta-spot group, will emerge? Why do complex regions preferentially produce CME/Flare?
- How do sheared neutral lines (filament channels) form?
- Is a filament channel a magnetic flux rope, or a sheared arcade or something else?
- Is there a relation between some feature of the sheared neutral line, such as length, magnitude of shear, etc. and a tendency to erupt?
- What is the magnetic structure of a sigmoid and why does it tend to lead to eruption?
- What is the magnetic cavity in the classical 3-part helmet structure?
- What are the differences in active precursors vs quiescent ones?
- What are the surface and subsurface dynamics? How is the energy content of the region changing?
- What is the origin of the hemispheric pattern of magnetic helicity?
- Are eruptive events a product of changes in the balance of fields of negative and positive helicity?
- What is the origin of the hemispheric pattern of magnetic helicity?
- Are eruption events a product of changes in the balance of fields of positive and negative helicity?
- What is the physics underlying disturbances in the corona (e.g. EIT waves, dimmings, shocks, Type II bursts)kicked up by CMEs? How do we interpret these signatures?

Science questions as collected in discussion
FLARES/CORONAL MASS EJECTIONS (CMEs)
(2) Why does an event happen?

- Is the energy for CME/flare stored in the corona or does it emerge through the photosphere during the event? If it emerges during the event, what are the observational signatures?
- If stored in the corona, is it all in the magnetic field, or is the gravitational energy of filaments and/or helmet structures important?
- Why does helmet streamer swelling sometimes precede CME/flare?
- Why does filament activation sometimes precede CME/flare?
- Why does enhanced soft X-ray emission sometimes precede CME/flare?
- Does flux cancellation/emergence play an important role in initiating CMEs/flare?

- Does magnetic reconnection play an important role in initiating CME/flare? If so, where does it occur and what are its observational consequences?
- What type of large-scale non-active-region magnetic structures are most likely to produce geoeffective eruptions?
- What is the physics underlying disturbances in the corona (EIT waves, dimmings, shocks IIs) kicked up by CMEs? How do we interpret these signatures?

Science questions as collected in discussion

FLARES/CORONAL MASS EJECTIONS (CMEs) (3)

(3) What will be the consequences? (How big and how fast?)

- Are there two physically distinct types of CMEs --- slow and fast?
- What determines the speed and mass of a CME?
- What is the magnetic structure of a CME in the corona, and what determines this structure --- the filament channel field, the overlying corona?
- What are the surface and sub-surface dynamics? How is the energy of the active region changing?
- Are there precursor indicators (magnetic field configuration, temperature, dynamics)?
- Are there two physically distinct types of flares --- eruptive and confined?
- Is flare heating due to magnetic reconnection?
- What determines the intensity and duration of the UV/X-ray emission from a flare?
- What determines the spectrum and intensity of energetic particles from CMEs?
- What determines the spectrum of these particles?
- How do these particles escape into the heliosphere?
- What energy is available in a specific region?
- What is the relative importance of intrinsic CME fields and compression and draping in situ in determining field strengths and field orientations in CME-driven disturbances at (say) 1 AU?
- How does structure of ambient solar wind affect evolution of CME-driven disturbances?
- How does structure within CME's observed optically relate to structure of CME's observed in situ?
- What is relative importance of magnetic and gas forces in determining evolution of CME-driven disturbances?
- What is the three-dimensional structure of CME-driven disturbances in the solar wind?

<u>Models and Observations</u>

Solar

Model Requirements

- 3D model of pre-CME/flare coronal field and plasma (closed and open)
- 3D model of eruption including effects of overlying coronal field
- 3D model of flare heating (reconnection)
- model for shock production and propagation
- model for particle acceleration

Observations

- Vector B field over whole solar surface (B measurements in corona if possible)
- Radio measurements of coronal magnetic fields
- high-resolution and high-cadence vector B and V in active regions
- high-resolution, multi-T imaging of chromosphere – corona from multiple viewpoints
- high time-cadence imaging and spectroscopy of CME/flare events
- chronograph observations below 1.1 R_Sun simultaneous with above and off the Sun-Earth line
- spatially resolved nonthermal X-ray observations
- helioseismology to observe pre-eruption
- Surface and sub-surface dynamics
- Solar irradiance as a function of wavelength
- Back side observations
- Polar observations
- Heliosynchronous observations
- Kilometric type 2 radio observations
- Direct radio observations

<u>Science questions as collected in discussion</u>

<u>Interplanetary Phenomena /Solar Particle Event (SPE)</u>

<u>(1) When is an event going to happen?</u>

CME Driven Events

- At what distances from the Sun are particles accelerated?
- How does one predict when the shock will arrive at 1 AU?
- How can Type II/IV radio bursts be used to better predict large SPE events?
- What determines when there shall be shock enhanced particle fluxes at 1 AU?
- What CME properties determine whether particle acceleration will occur?
- What properties of the interplanetary medium affect particle acceleration?
- How can electrons be used as a diagnostic tool?

<u>Flare Events</u>

- What magnetic signatures can help predict SPE magnitudes?
- How do we relate Type III bursts to particle fluxes at Earth?

- What determines the fraction of accelerated particles that escape from the Sun?

<u>Science questions as collected in discussion</u>

Interplanetary Phenomena/Solar Particle Event (SPE)

<u>(2) What will be its consequences (How big and how fast?)</u>

CME-Driven Events

- What material is accelerated?
- What determines the energy spectra of the accelerated particles?
- What determines whether a given SEP event is Fe-rich or Fe-poor?
- Origin of highest energy Solar Energetic Particles (SEP) (~1GeV) flares or shocks? (How to accelerate to >1 GeV)
- What are the spectral characteristics (energy and composition) of a plausible "worst case" event? (analogous to a 100 year or 500 year flood prediction)
- What are the spectra of alpha and high-energy, heavy ions produced by these events and how can they be predicted?
- Given that a particular proton spectrum (say 10/89, 8/72, 07/00 events) produces doses that are biologically of concern, what precursor conditions are reliable predictors of the occurrence of these events?

Flare Events

- What is the nature of the acceleration mechanism?
- What material is accelerated?
- Are there hybrid events with superposed flare and CME accelerated particles?
- What fraction of the accelerated particles escape?

<u>Science questions as collected in discussion</u>

Interplanetary Phenomena/Solar Particle Event (SPE)

<u>(3) How big and how long will be event be? (Consequences)</u>

<u>CME-Driven Events</u>

- What determines how long particle acceleration continues as the CME moves outward?
- How do CME's evolve with distance from the Sun?
- What electromagnetic diagnostics can improve forecasts of SEP events?
- Where along the shock-front are particles accelerated?
- How does magnetic field topology affect particle transport to Earth?
- How do solar particle fluxes depend on radius from the Sun?
- What are 3-D characteristics of the CME and how do they propagate?
- Is there a maximum possible flux of particles of a given energy?
- Are SEP events larger if there is a pre-existing population to accelerate?
- What is the latitudinal extent of the accelerated particles?
- What properties of the IPM lead to geomagnetic cutoff variations?

<u>Flare Events</u>

- How can electrons be used to forecast SPE consequences?
- What is the longitudinal extent of flare-accelerated particle fluxes?

Science questions as collected in discussion

Interplanetary Phenomena/Geomagnetic Storms

(1) When is an event going to happen?

- How well do structures measured at L1 translate to the magnetosphere (fidelity of L1 data)?
- What interplanetary parameters correlate with the sigmoid characteristics?
- What interplanetary parameters correlate best with geomagnetic storms?
- What geomagnetic conditions/indices lead to cut-off variations?
- What interplanetary conditions/events lead to the formation of new radiation belts?
- How far upstream of L1 can a monitor be effective?

Science questions as collected in discussion

Interplanetary Phenomena/Geomagnetic Storms

(2) Why does the event occur?

- What is the structure of the near-ecliptic heliosphere inside 1 AU?
- What is the role of field-line draping in determining the geoeffectiveness of a CME?
- Where do flux ropes originate and what role do they play?
- What is the role of non-rotating stream interactions in producing geomagnetic disturbances?
- How do interplanetary structures interact with the magnetosphere?
- Is the abundance of Helium important?
- How do large-scale structures such as CME's (including the magnetic topology) evolve w/ distance?
- What is the global structure of non-CME, non-rotating disturbances?
- How do the interplanetary medium and magnetosphere interact?

Science questions as collected in discussion

Interplanetary Phenomena/Geomagnetic Storms

(3) How long will the event last?

- What interplanetary parameters determine the size and duration of the storm?

Models and Observations

Interplanetary

Models

Interplanetary Phenomena/Solar Particle Event (SPE)

- Particle acceleration models
  - CME-driven shock acceleration from 1 solar radius to 1 AU.
  - Acceleration and escape in flares
- Particle transport to 1 AU, including wave-particle interactions and magnetic field topology
- CME transport through Interplanetary Medium (IPM)

- Geomagnetic field cutoff variations

Geomagnetic Storms

- CME transport and evolution from 2 R-Sun to 1AU
- CME interaction with the magnetosphere
- Injection and formation of radiation belts

Observations

- Need multi-spacecraft observations of in situ characteristics of particles, plasma, and fields
  - As a function of radius (0.2 AU to 1 AU)
  - As a function of longitude (especially east of Earth)
  - To high latitude
- To understand the evolution and structure of CMEs need multipoint in situ measurements combined with stereo (or more) (STEREO) imaging. Most important dimension is radial, then longitudinal, then polar.
- Key measurements for spacecraft that leave 1 AU:
  - Magnetometer—standard
  - Plasma: p, He, electrons (ρ, v, T)
    + Composition
    + Suprathermals
  - Particles: 0.03-1 MeV/nucleon--p, e, composition; 1-100 MeV/nucleon—p, He, e, composition; 100-1000 MeV/nucleon—good to have, not essential if weight limited.
  - Radio telescope: 20 Hz-4 MHz
  - Plasma wave?
- Heliospheric Imaging
  - 2-D Heliospheric imagers
  - or 3-D Heliospheric imagers
  - 2-D mapping of radio bursts
  - or 3-D mapping of radio bursts
- Would like more than a single point measurement from L1; better to have multipoint measurements to determine structure of CMEs.
- Would like near-Earth spacecraft in front of the bow shock to check the fidelity of the projection from L1 to Earth.
- At L1 and inner-heliospheric sentinels
  - 1 s time resolution of B vector
  - 1min time resolution n,V,T
  - 10s energetic ion and electrons (10keV-300MeV)
  - 10s radio waves

Science questions as collected in discussion

Magnetosphere/Ionosphere

Energetic Solar Particles (D region ionization and radio wave absorption) (determined by solar event)

- What is areal extent of the event?
- What is flux and spectrum of the protons?
- Duration of the event?

MEASUREMENTS
Magnetosphere / Geomagnetic Field Variation

- Why are there substorms?
- Origins of field line currents?
  - What determines the FAC magnitude?
  - What determines their distribution?
  - Where are they closed?
- What is auroral electrojet location / strength?
- What is the Auroral conductivity?
- What determines the size of the polar cap?
- What determines the polar cap potential?
- What is physics at far end of the field lines, role of reconnection in determining polar cap potential?
- Origin Ring current?
- What determines the temporal and spatial development of the ring current?
- What produces injection events? And are they coupled to currents?
- What is the source of mass for the magnetosphere?
- How compressed is the geomagnetic field during a storm?
- For how long?
- What is the role of feedback between the ionosphere and magnetosphere?

MEASUREMENTS
Plasma Environment @LEO, MEO, GEO

- What is the source of ionospheric plasma in the magnetosphere?
- What is the structure of the plasmasphere during and following a geomagnetic storm?

- LENA imaging of plasma sphere

- Plasma dynamics and neutral dynamics coupling in Polar Cap / equator
- What is the source of variability for the equatorial ionosphere?

MEASUREMENTS
Ionospheric Storms Caused Through Solar Wind-Magnetosphere Coupling

- How does the global ionospheric system respond to energy dissipation?
- How is the polar cap ionosphere structured and evolve?
- What is the ionospheric response to fast solar spectral changes?
- What are the triggers and dampers for ionospheric irregularities? What is their morphology / dynamics?
  - Polar cap- how is plasma structured from 100 km to 1 m?
  - Auroral- what is the role of particle precipitation vs. electric fields vs. waves?

- Mid-latitude- how does auroral trough and disturbance electric field produce irregularities.
- Equatorial- How is initiation of equatorial spread-F influenced by neutral winds, gravity waves, penetrating electric fields, SAA origin electric fields, TID's
- What are the processes in MI coupling specific to storms?
- How much energy is exchanged between the thermosphere and ionosphere during storms?
- Where and when is the exchange important?
- How the global IT system responds to this global dissipation?
- Data assimilation and what are our limits to forecasting?
- TEC issues -Impact of advection and bulk transport on TEC structure? Role of particle precipitation in determining TEC?
- Further Issues generally needing to be understood:
  - Reconnection
  - Particle acceleration
  - Turbulence
  - Shock generation
  - How the solar wind coupled to the magnetosphere
  - How does the mass enter the magnetosphere from the solar wind?
  - How is magnetospheric energy dissipated?
  - What happens when nature pushes the plasma beyond its capability to carry current?
  - Inner magnetospheric particles and fields

Science questions as collected in discussion

Neutral Atmosphere Variations from Solar Wind-Magnetospheric Coupling

- How does the IT system respond to particle precipitation and joule dissipation?
- What is the origin and how do traveling ionospheric disturbances propagate?
- Drag and variability-- How does the neutral density change on fast time and short spatial scales.
  - What causes these changes?
  - How does atmospheric scale height vary?
- How does the upward propagation of waves from the lower atmosphere effect global electrodynamics and low latitude ionospheric variability?
- How does the neutral atmosphere respond to changes in the solar spectrum?

Models and Observations

Magnetosphere/Ionosphere/neutral atmosphere

Models

- Specification models: Establish highly accurate ionosphere/thermosphere parameters for baseline measurements.

  - Global characterization and understanding of the ionosphere/upper atmosphere (100-1000 km) and its connection to the sun, solar wind, and magnetosphere.
  - Major improvements of ionospheric and thermospheric specification models.
- Improved models for forecast and "nowcast" accuracy.
- Physical Models: Fully specify and understand ionospheric and thermospheric properties.
- Improved models will provide enduring knowledge that will effectively address all space weather issues

- 4-D data assimilation models

<u>Observations</u>
- Image large-scale plasma structures in the polar cap, auroral oval, mid-latitudes, and equatorial ionosphere.
- Image auroral oval and precipitation
- In situ measurements of plasma density, drifts, density structuring, and temperature, neutral winds and electric fields
- Two-frequency radio beacons
- Several polar orbits and two equatorial orbits
- Inner magnetosphere influence on SAA and possible ionospheric impact
- Multiple spacecraft on both equatorial HEO and polar LEO
  - 1s time resolution B vector
  - 10s time resolution thermal plasma distribution function
  - 50eV-40KeV w/ composition
  - 10s time resolution energetic ion (40KeV-300MeV w/composition)
- Inner magnetosphere S/C obs
  - Latitude/L : L=2 to 8
  - E field
  - energetic particles (p sheet)
  - thermal particles (Ne, H+, O+)
  - radiation belt particles
- Thermospheric density, temperature and winds, mesospheric winds and flows
- Thermal and radiation belt energies
- Electric fields, plasma drifts
- Neutral winds
- Focus on boundaries, sub auroral trough
-
- SW Bz and Pressure
- Ionospheric TEC and 2-D structure
  - M-1 coupling (plasma process) sensors for RC energized
  - RC/plasmasphere interactions processes

- Global imaging of the disk and limb of the Earth on a continuing basis
  - EUV (ionosphere)
  - FUV (thermosphere)
- Continuous in situ measurement of atmospheric neutral density in the thermosphere below 500 km
- Solar EUV irradiance vs. wavelength

REPORT OF WORKING GROUP 2 (WG2) -- Space Storms (Medium Time Scales)

Science questions, mission goals, and derived observables as formulated following a community-input workshop held on 31 January 2001, in Greenbelt, MD, and subsequent iterations.

This material primarily applies to "Group II: Intermediate time scales" (with specific focus on fast solar wind streams and geospace responses, ionospheric scintillation, (sub)storms, and atmospheric drag), but more general notes have been added.

About this document

This document contains processed notes from the community-input workshop on the LWS Science Architecture. It is mostly focused on Group II on Intermediate Time Scales, but some pages reflect parts of the discussions of later pages. The emphasis on those pages is more solar / heliospheric, merely reflecting my homework assignments at the meeting.

STATUS of this document: Note that the ionospheric and upper atmospheric physics were moved to Group I during the meeting, and hence it is poorly represented in this section!

I have introduced a few pages that reach well beyond Group II:

– Some general comments about the program's science and relative research status.
– A wire diagram attempting to show the complex interconnections of LWS
– A list of (some of) the themes common to the LWS sub-disciplines.
– Matrices of how the required models and observables for Sun and heliosphere connect to the space-weather impacts on society; other SAT members are working on complementary tables for geospace.

<u>Some introductory remarks</u>

The implementation and goals of the LWS program ("address those aspects of the connected Sun-Earth system that directly affect life and society") need to reflect the different stages of development of the sub-disciplines that are involved. For example:

• forecasting of solar events (flares, CMEs, ...) is yet to be put on a quantitative footing,

- the mechanism(s) by which solar activity affects Earth's climate remain unknown,
- the upper-atmospheric, ionospheric, magnetospheric communities appear to be much closer to quantitative specifications and forecasting models than solar & heliospheric and Sun-climate communities.

Moreover:

- LWS also includes aspects on the non-variable space weather, i.e., those phenomena that are a consequence of the rotation of the Earth, including both its (upper) atmosphere and (extended) magnetic field
- The physics of the coupling between solar photosphere, chromosphere, corona, and inner heliosphere is differentiated into sub-disciplines similar to that of the coupling between heliosphere, magnetosphere, ionosphere, and neutral atmosphere, but this differentiation is not reflected in this document.

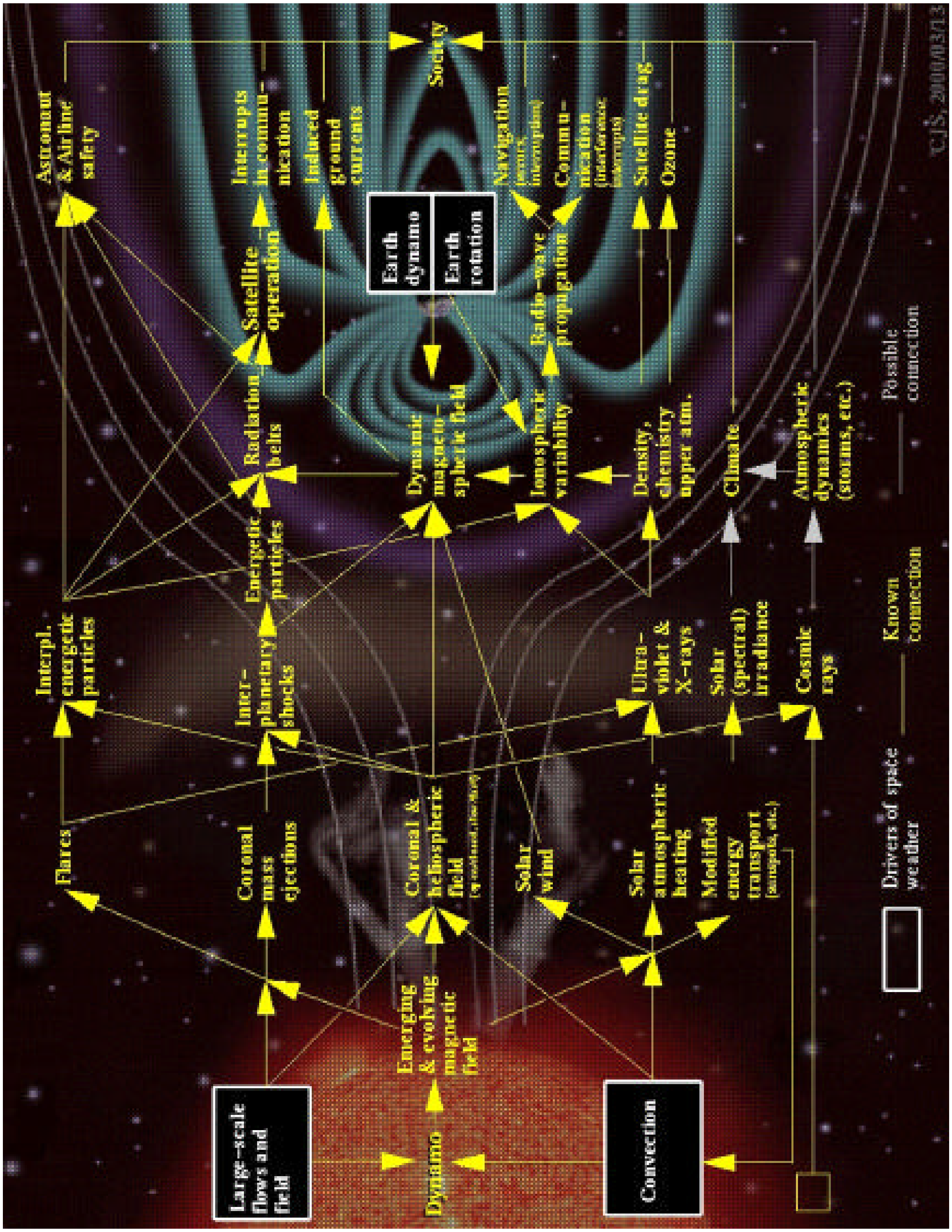

Fig. 1. Sketch of space weather drivers and their linkages.

Note: a jpg version of this figure is at the following web site:
http://sampex.umd.edu/docs/lws/workshopfig1.jpg

Some common themes

Themes and discussion issues that cross the traditional discipline boundaries:

- Particle acceleration in shocks
- Magnetic reconnection and plasma heating
- Wave-particle-field interactions
- Data assimilation into models
- Tradeoff: imaging versus spectroscopy
- Tradeoff: space-based versus ground-based
- Differentiation: SEC-general versus LWS-specific
- Expectations: future missions versus present missions
- Data visualization (theory & observation)

Sun: interior, surface, corona

Science goals (not prioritized):
To understand
- whether specific flow patterns or lasting structural changes in the solar convective envelope can be recognized in relation to active-region emergence, and in particular to active sites (nests). If so, longer-term forecasts are possible.
- how magnetic field emerges onto the surface and how it interacts with existing field;
- the large-scale dynamics of the magnetic field in the solar corona and inner heliosphere, specifically the physics of reconnection, dissipation, and electrical currents that are relevant to the large-scale restructuring of the coronal magnetic field;
- (empirically and theoretically) how to extrapolate the surface field ;
- the interaction of the internal and near-surface solar structure and the solar magnetic field leading to generation of mass ejecta and associated energetic particles, and the release of these into the heliosphere;
- the radiative output of the entire solar atmosphere (particularly in the UV for our time scale), including the identification of proxy measures;
- the coupling between the high-density photosphere and field-dominated inner corona, and the coupling between the field-dominated corona and the flow-dominated inner heliosphere.

- **Forecast goals**:
  (1) detection of large active regions prior to emergence (if possible)
  (2) multi-day forecast for coronal mass ejections
  (3) accurate one-day forecast for major flares
  (4) forecasting of solar (spectral) irradiance

(5) forecast of the large-scale coronal and heliospheric field (including coronal holes)
(6) forecast formation of filaments, unipolar areas, and other large-scale features as a consequence of flux transport processes - features involved in eruption triggering and propagation

- **Areas in which fundamental knowledge appears to be missing:**
  (1) The potential of detecting some helioseismic signature of emerging active regions
  (2) the triggering mechanism of flares and CMEs (does its physics allow accurate long-term forecasts?)
  (3) emergence of field through the topmost layers of the convective envelope
  (4) reconnection physics
  (5) scale coupling
  (6) wave-particle-field interactions from particle to fluid scale (including heating)
  (7) field dispersal and the possible coupling to a small-scale dynamo
  (8) cause and effect of rotational shear zone immediately below the surface..

Heliosphere

Science goals (not prioritized):
To understand:
- the dynamics of the heliospheric magnetic field in response to the dynamic inner coronal field; in particular understand how eruptive events interact with downstream medium, and how the latter evolves in space and time
- the acceleration and heating of the solar wind, including the differentiation by ionic species
- the evolution of and interaction between wind streams,
- the interaction of CMEs with the heliospheric structures within which they travel, as well as the internal evolution of CMEs.
- the formation and propagation of shocks and the way in which they accelerate particles
- the evolution of field structures (including flux ropes) in the heliosphere
- the propagation of cosmic rays

- **Forecast goals**:
  (1) forecast of the evolution of the magnetic field in the interplanetary medium, with particular emphasis on the Bz component of the

field at the leading edge of the perturbation just ahead of the Earth's magnetosphere
(2) improved the prediction of the probability and impact-time forecast for high-speed wind streams striking the magnetosphere
(3) computation of the heliospheric field to compute solar and galactic cosmic-ray transport

- **Areas in which fundamental knowledge appears to be missing:**
  (1) The physics of wind heating and acceleration
  (2) the coupling of the low-β corona to the high-β wind
  (3) shock-particle interaction
  (4) turbulence.

<u>Observables: Sun / Heliosphere</u>

- Dynamics of the coronal magnetic field, using emission as tracers: –Full-Sun imaging, resolution of 1 arcsec or better, 5-10 s cadence or better, simultaneously covering the temperatures from at least 0.1MK up to 10MK (both with narrow-band EUV and broader-band X-ray optics).
- Surface magnetic field on as much of the solar surface as possible (at least the full disk, including near limbs -in particular polar regions), possibly from multiple viewpoints if more than a few days forecasting is required (eastern hemisphere view).
  – Vector magnetic field, of order 1 arcsec resolution, high sensitivity
  – Both photospheric and mid- to high-chromospheric fields are needed.
- High-coronal field measurements in order to validate extrapolation models
  – Preferably over disk regions, by an instrument near quadrature. Off-limb will be useful for initial studies (perhaps feasible from the ground using white-light and / or perhaps radio). Field-strength measurements (spectroscopic methods) deemed useful, but line-of-sight confusion recognized as a significant problem.
- Spectroscopic measurements to establish properties of coronal plasma
  – Off-limb for wind physics; on-disk for field reorganization
  – Measure: ion temperatures, composition, ionization states, velocities, …
- Seismology to image backside activity (for longer-term or high-precision forecasts)
- Solar EUV (0-200nm) irradiance for upper-atmospheric (60km and higher) studies (at 10A resolution).
- Coronagraphic observations to study the properties of the low solar wind: field geometry, acceleration

  - white-light, 1.5 solar radii, preferably to 30 solar radii (tradeoff study needed)
- Spectroscopic measurements to establish properties of heliospheric plasma
  - Measure (off limb): ion temperatures, composition, ionization states, velocities, …
- Heliospheric plasma properties at quadrature to compare to model results
  - Composition, basic plasma properties. Field measurements TBD.
- Particle fluxes and field properties before bowshock (preferably just upstream from magnetopause and at or upstream from L1) and also closer to the Sun

Theory / models: Sun / Heliosphere

- 3D model for coronal field and plasma
- Model for transient initiation (CME, flare, …)
- Comprehensive field-dispersal model for the solar photosphere
- 3D model for rotationally varying coronal-heliospheric field and plasma
- (Shock) Model for energetic particle production in the heliosphere
- Dynamic heliospheric model (**B**, n, p, …) including CME propagation

Magnetosphere

Science goals:
To understand:
- how to predict the magnetospheric conditions from the time history of solar wind parameters, including situations with well-defined high-speed streams, CMEs, and interplanetary shocks,
- how geomagnetic storms couple into the dynamics of the ionosphere, and how the ionosphere affects the magnetosphere,
- the life cycle of energetic particles and magnetospheric plasma,
- the coupling of the magnetosphere to the atmosphere and ionosphere,
- the relative roles of internal and external forcing,
- particle acceleration in shocks
- the acceleration and transport of particles in the magnetosphere,
- structure and dynamics of the Earth's plasma sheet, which is the principal source of the aurora and the energetic particles trapped in the inner magnetosphere,
- how energy flows down from the magnetosphere to form the aurorae.

N.B. Both the inner magnetosphere (within which field lines close back to Earth, and which lies equatorward of the auroral zones) and its complement need to be adequately addressed.

• Forecast (eventually)/Nowcast (more immediate need) goals:

(1) magnitude, duration, and expected effects on the ionosphere and neutral atmosphere of the changes in the particle populations affected by (recurrent) geomagnetic storms
(2) forecasts of particle and plasma environment redistribution caused by CME events
(3) expected atmospheric and ionospheric effects of geomagnetic evolution
(4) induced ring and ground currents
(5) magnetopause compression
(6) cosmic-ray cutoff.

• **Areas in which fundamental knowledge appears to be missing:**

(1) particle transport in the inner magnetosphere, both diffusive and non-diffusive
(2) large-scale current systems
(3) effects of ionospheric changes on magnetospheric dynamics
(4) storm-substorm relationship
(5) relativistic electron acceleration and transport
(6) 3d geomagnetic field
(7) complete but tractable model for individual particles and fluids, including currents
(8) mass source of magnetosphere and especially magnetotail
(9) mass-momentum coupling to lower altitudes;

Ionosphere

Science goals (not prioritized):

To understand:

- the effects of solar UV radiation on the ionosphere and on the neutral atmosphere
- the feedback of the ionosphere on the generation of field-aligned currents (initiation of substorms).
- ionospheric response to flares
- relative roles of direct versus indirect coupling of ionosphere to solar variability (irradiance versus solar wind)
- Electron acceleration and transport, both diffusive and non-diffusive
- Access of very energetic particles to the ionosphere
- Substorm injections of hot plasma
- Ring current acceleration and transport, effect on global magnetic field
- Magnetic reconnection during major storms
- Wave-particle interactions, and effects on acceleration and transport
- Causes of ionospheric irregularities
- Effect, on the development of a storm, of the pre-existing state of the magnetosphere and ionosphere
- Penetration of magnetospherically driven electric fields to the low-latitude ionosphere
- Upward acceleration of ionosphere ions and mass loading of the magnetosphere
- Ionospheric currents
- Particle precipitation

• **Forecast goals**: ...

• **Areas in which fundamental knowledge appears to be missing:** ...

Observables: Geospace

- Global (multipoint), fluctuating magnetic and electric fields
- Auroral imaging and measurements of polar-cap size from high-inclination orbit
- Magnetic and electrical fields, and plasma conductivity in ring current, magnetopause current, and auroral current systems
- Hot plasma injection and cold plasma density forming plasmasphere and Alfvén layers
- Radiation belt fluxes (electrons, protons)
- Ionospheric matter coupling to magnetosphere (mass loading & precipitation)
- Neutral winds (>60km)
- Ionospheric electric fields and electron density
- Aeronomy (including O_2/N_2 ratio)
- Atmospheric transport of energetic particles to stratospheric heights (from balloons)
- Solar wind time series at magnetopause (n, V, B, ram pressure)
- Particle flux (or phase space density) as function of three adiabatic invariants or L, local time, and equatorial pitch angle
- Solar proton, He, and heavy ion fluxes
- Energy flux (in charged particles precipitating into ionosphere?)
- Geomagnetic cosmic ray cutoffs
- Polar cap size

Note: There will be lots of tradeoffs in terms of spatial and temporal coverage. Seeing acceleration in the rare but important event of a shock wave passing through the magnetosphere would be best accomplished by spacecraft providing constant coverage at 2 or 3 R_E geocentric distance, near the equatorial plane. Low-Earth orbit is best for monitoring radiation at International Space Station or inputs to the ionosphere and atmosphere. Defining the mechanism that accelerates electrons to relativistic energy requires measurement of phase space densities at multiple L-values. Modeling will play an important role in resolving all of these issues

Theory/models: Geospace

- 3D geomagnetic field model
- Single-particle transport codes for magnetosphere Global magnetospheric model
- Model for radiation belt and ring current
- Global coupled thermosphere-ionosphere model
- Dynamic ionospheric irregularity model
- Model for ionospheric driving by solar irradiation

- Coupled ionosphere-atmosphere model
- Wave-particle interaction models

Atmosphere and global climate

• Science questions:

What are the important mechanisms for the solar UV input as a function of wavelength and as a function of altitude in the Earth's atmosphere?

Ozone chemistry (upper-atmospheric aeronomy)

• What are the largest gaps in our knowledge and understanding of the manner by which solar electromagnetic radiation and the several manifestations of solar activity (for example interplanetary sector boundaries) couple to the neutral atmosphere? Do we understand, in a quantitative way the role of the magnetosphere in affecting the properties of the neutral atmosphere, for example via precipitating electrons? How well do we understand, in a quantitative way, the coupling between the ionosphere and the neutral atmosphere?

Study topics & general comments

- High priority: continuity of measurements, because the instantaneous state of the solar/heliospheric field depends on past generations of active regions, their evolution, the coronal field response, and the sequence of perturbations having traversed the heliosphere.
- High priority: simultaneous coverage of Sun/inner-heliosphere system, and of magnetosphere/ionosphere system (including solar wind and(E)UV input).
- High priority: complete coverage from solar surface to at least ~30 solar radii. Specifically: any coronagraphic imaging must reach down to at least 1.5 solar radii, preferably even lower.
- Need to explicitly address effects of ``internal'' effects of ionospheric evolution on magnetosphere.
- Multiple viewpoints crucial for the proper validation of results from modeling efforts, specifically: quadrature particle measurements and WL coronal imaging, and upstream solar-wind properties..
- Tradeoff study of scientific return vs. coronagraphic field of view.
- High priority: need feasibility study to establish the potential of seismic imaging of new active regions if forecast potential of more than a few days is needed.

- Need a study to establish the feasibility of coronal field-strength measurements
- Seek advice on potential of chromospheric vector magnetograph
- Seek advice on the potential that small-scale and / or weak solar fields play a crucial role in large-scale field physics.
- Need ``wire diagram'' to show all (multiple) links & (nonlinear) processes -- see Figure 1

Table WG2-1: Required obs.: Solar

Topic: (see key below)	1	2	3	4	5	6
	Global Clim	SPE	Mag storm	Now cast	Pred Env	Space Clim
EUV/X-ray imager	N	Y	Y	Y	Y	
Surface vector B	.	Y	Y	.	Y	.
Chromosphere. B	N	Y	Y	.	Y	.
High-coronal B	N	Y	Y	Y	Y	.
Coronagraph	N	?	Y	.	Y	N
Coronal spectr. (disk)	N	Y	Y	.	Y	N
(of limb)	N	Y	Y	Y	Y	Y
Seismology	Y	?	Y	N	Y	Y
surface flows	Y	Y	Y	N	Y	Y
EUV spectral irrad.	N	.	N	Y	N	Y
Total irrad. monitor	Y	N	N	N	.	Y
Irradiance imager	Y	N	N	.	.	Y

Key to topics
1) Solar influences on global change
2) Solar Proton events
3) Geomagnetic storms
4) Nowcasting space environment
5) Predicting space env.
6) Space climate

Table WG2-2: Required models: Sun & Heliosphere

This page lists the relevance of each required model to the space-weather impact. Note that it only applies to Sun & heliosphere; other discussion groups addressed the complementary tables.

Topic: (see key below)	1 Glob Clim	2 SPE	3 Mag storm	4 Now cast	5 Pred Env	6 Space Cllim
Model of the instantaneous corona & inner heliospheric field based on (vector) magnetic field measurements	N	Y	Y	Y	Y	Y
Dynamic coronal model to study CME development & propagation model	N	Y	Y	...	Y	Y
Solar-cycle model	Y	N	...	N	Y	Y
Models to link proxies of activity to EUV, UV, total irradiance.	Y	N	N	Y	Y	Y
Surface flux-dispersion model	Y	Y	Y	Y	Y	Y
Transient initiation model	N	Y	Y	Y	Y	...
Particle acceleration model	N	Y	...	Y	Y	...
Solar-wind acceleration	Y	Y	Y	Y	Y	Y

Key to topics
1) Solar influences on global change
2) Solar Proton events
3) Geomagnetic storms
4) Nowcasting space environment
5) Predicting space env.
6) Space climate

Table WG2 - Table 1. Space weather on intermediate time scales; causes, consequences, processes (post-workshop)

Source →	Solar AR emergence or field evolution -- Solar field dispersal, large-scale reconnections, destabilization -------------								
Propagation ↓	Flare erupt-ion, along helio-spheric field	Solar UV irradi-ance	Evolving global sector structure (including solar cycle hysteresis) within which disturbances (e.g. CMEs) propagate						
Process → Impact ↓	Solar Energetic Particles and (E)UV	Iono-spheric & neutral-atm. effects from solar UV	Radiation Belt Enhance-ment (Electrons & Protons)	Magnetosphere/ Geomag-netic Field Variation	Orbital Plasma Environment (from responses to wind and (E)UV)	Iono-spheric Storms Through Helio-Magnetosphere Coupling	Iono-spheric Effects from Energetic Solar Particles	Neutral Atmo-sphere Varia-tions from Helio-Magneto-spheric Coupling	Cosmic-ray modu-lation
Loran Navigation System outages	R1						I3		
Impacts on launch vehicles enroute to orbit	R1	**						N1	
Astronaut/ Airline Radiation	R1		R3	M1					
Satellite Operations	R1	**	R3,R4	M2	P1			N1	
SEU/Latchups; deep dielectric charging; surface charging; total dose	R2		R2,R3		P1				
Interference on Defense moni-toring systems	R1		R4			I1	I3		
Induced volt-ages and outages on power systems, con-ductors				M3					
Interruption of Satellite to Ground Communica-tions; Disruption of or errors on GPS navigation systems		**				I1			
Interrupted communication (HF ground-to-ground & air-to-ground; cell phone; radio)						I1	I3		
Weather (Climate)		**			W1		W1		W1

List 1. How environmental variations affect systems (draft)

R1— Solar energetic particles, including protons and high-Z particles, are a radiation hazard to astronauts in space and to a lesser extent, to crews and passengers on high flying aircraft. For Space Station missions and aircraft, the hazard is more severe over the polar caps regions where the particles have direct access along open magnetic field lines. The particles can cause radiation damage to components causing an effect labeled single event upsets or can cause degradation and loss of efficiency of solar power panels. They also may penetrate optical sensing systems to produce snow-like noise. In the longer-term picture, there are likely to be aerospace planes or other means of transportation and dense that going into orbital altitudes for portions of their flight. Future flights to the moon and other planets are particularly vulnerable to radiation effects on crews and systems.

R2— High-energy electrons penetrate into satellites and produce charging that can suddenly discharge and damage or impair satellite operation.

R3— Enhancement and decay of radiation belts increase exposure to energetic charged particles for astronauts and hardware in Earth orbit. The impact is especially significant at International Space Station altitudes but extends to higher orbits as well. (This impact overlaps R2 and might be combined with it).

R4— High radiation particle background rendering operational sensors inoperative (e.g., x-ray, CCD).

M1— Increased extent of open field lines in Earth's polar cap regions lead to added radiation exposure in high-inclination orbits and on high latitude, high altitude aviation flight paths. The phenomenon differs from the process by which protons and ions are accelerated and controlled in the solar wind.

M2— During geomagnetic storms, the magnetosphere may be compressed to inside geosychronous orbit and the maintenance of orientation of satellites using magnetic torquers may be impaired.

M3— Currents in the atmosphere induce currents in the ground which in turn and cause currents in long-distance conductors such as power lines and pipelines.

P1— Surface charging on satellites may reach sufficient levels to produce high voltage discharges that damage or impair satellite operation

I1— Ionospheric storms in the F-region can cause scintillation, signal delay, or temporary signal loss

I3— Energetic protons raining on the topside of the ionosphere in polar regions produces D-region enhancement and blacks out high frequency radio communications and radar signals.

N1— Atmospheric heating from currents causes the atmosphere to expand so that satellites experience greater atmospheric density and increased drag on its orbital motion.

W1— Modulation of the current density in the global electric circuit affects cloud microphysics, affecting cloud albedo, storm intensity and storm tracks.

List 2. Sequential list of storm phenomena connecting the Sun to the Earth

Intermediate Time Scales (Storms) Relevant Physical Processes

"Intermediate" = 10^0-10^3 hours
Intermediate time scale processes are maybe 99% of the time
Explosive processes give the extreme conditions (in some cases – e.g. not high speed streams)
Climate time scale processes are defined in part by the average and standard deviation of intermediate time scale processes

Solar features and structures (with persistent characteristics -- these features/structures provide some advance warning or predictability, including recurrence)

- active regions (have sufficient predictive value that SEC numbers them)
- equatorial coronal holes (produce the most extreme radiation belt events)
- streamer belts & heliospheric current sheet structure

Solar wind features and structures

- bulk parameters including density, pressure, velocity, temperature, Bz
- co-rotating interaction regions (CIRs)
- high-speed solar wind streams
- strong, but perhaps short-lived, Bz-south / statistical characteristics
- Alfvén wave trains - HILDCAs

Solar Wind-Magnetosphere Interactions

- bow shock location and dynamics; e.g upstream ULF wave production
- solar wind to magnetosheath transitions (what hits the magnetopause?)
- magnetopause stand-off distance and shape
  + boundary conditions for internal magnetospheric dynamics (esp. MHD)
  + magnetopause compression events, magnetic torquing & navigation
- solar wind/magnetotail parameter correlation
  + e.g. super-dense plasma sheet conditions

Internal Magnetospheric Processes
- Global magnetic field structure that dictate particle dynamics & coordinate system itself
- Global electric field structure and transport from tail to inner magnetosphere
- Ring current injection -> effect on magnetic field -> effect on particle dynamics
- Diffusive processes & time-dependent E & B fields
- Wave-particle interactions
  + direct heating
  + radial diffusion
  + pitch angle diffusion and resulting ionospheric precipitation

Magnetosphere-Ionosphere Coupling
- Global convection electric fields
- Electrojet and ground-induced currents (relation to field aligned currents)
- Particle precipitation & ionospheric irregularities (scintillation)
  + e.g. SAR arcs
- Joule heating

Ionospheric Processes, direct solar coupling, and Ion / Neutral / Climate
- Radiation exposure in the polar cap and South Atlantic anomaly
- Energy input into the atmospheric auroral zone
- High latitude and equatorial current systems
- Neutral atmosphere heating
- neutral winds
- drag

Coupling to Stratosphere and Troposphere
- Stratospheric and tropospheric conductivity modulated by cosmic-ray flux and Bremsstrahlung X-rays.
- Global electric circuit links cloud microphysics with ionospheric potential and middle atmosphere conductivity changes.

REPORT OF WORKING GROUP 3 (WG3) -- Space Environment (Long Time Scales)

1. Identify and Quantify the Earth's near-surface temperature changes attributable to solar variability.

- Establish the relationships between historical proxies and solar radiance.
- Identify solar fingerprints in climate records
- Validate models of climate response to solar forcing.
- Begin an initiative to understand the factors controlling total solar irradiance.

2. Identify and Quantify the changes in ozone distribution attributable to solar variability.

- Validate models of ozone distributions from inputs specifying solar UV and particle inputs.
- Begin an initiative to understand the factors controlling the solar UV spectrum.

3. Advance the capability to specify and predict the hazardous particle environment.

- Establish a data collection network and assimilation models
    - L1 Interplanetary environment
    - Energy Spectrum of electrons 300 keV - 30 MeV protons 5 - 500 MeV
    - Magnetospheric magnetic field vector.
- Produce a statistical climatological model with spatial dependence over time scales from minutes to decades.

- Quantify the acceleration mechanism for outer zone MeV electrons.

4. Produce the capability to specify and predict the large-scale behavior of the ionospheric density from 100 to 1000 km,

- Establish data assimilation procedures for disparate data sets describing the ionospheric density.
    - Ground and GPS TEC measurements from existing networks
    - Ionosonde and ground-based radar measurements defining the bottomside
    - Ionospheric density and temperature from available s/c
- Create an empirical model of low and middle latitude neutral winds driven by solar and magnetic activity.
    - L1 interplanetary environment

Global distributed neutral wind measurements between 300 km and 600 km
Wave amplitude and phase velocity in the lower thermosphere.
Solar EUV spectrum
GCM for specification of major oscillation modes.

- Create a physics based assimilation model of the large-scale high-latitude ionospheric electric field driven by specification of the interplanetary environment.
  - Magnetic perturbations and e-field measurement inputs to assimilative models.
    - Ground-based magnetometers
    - Superdarn radar
    - e-field and magnetic perturbations from available s/c.
  - L1 interplanetary environment
  - Needs to improve global M-I coupling model.
- Create an assimilative model of the large-scale mid and low-latitude ionospheric electric field driven by specification of the interplanetary environment solar EUV
  - e-field or ion drift measurements distributed in longitude.
- Create an assimilative model of the high latitude auroral particle input.
  - Particle input from in-situ satellites
    - DMSP/NPOESS others
  - Global imaging for longitude structures
- Begin an initiative to understand the factors controlling the solar EUV spectrum.
  - Full disk measurements of EUV spectrum
  - Solar dynamo

5.Produce the capability to specify and predict the mass density of the atmosphere between 300 and 600 km altitude with accuracy better than 10%

- Establish data assimilation procedures for disparate data sets describing the neutral mass density.
  - Neutral density profiles from available s/c
  - L1 interplanetary environment
  - Solar EUV spectrum
  - GCM for specification of major oscillation modes.
- Determine the influence of tropospheric waves on the upper atmosphere.
  - Wave amplitude and phase velocity in the lower thermosphere.
- Create an empirical model of neutral density driven by specification of solar EUV and the interplanetary environment.
  - In-situ measurements of neutral composition 300 - 600 km
  - Particles, fields, and drifts to define magnetospheric influences
  - L1 interplanetary environment
  - Solar EUV spectrum

6. Produce the capability to forecast the intensity and location of ionospherically induced currents at the ground.

- Create a Magnetosphere-Ionosphere coupled model with ionospheric scale processes driven by specification of the interplanetary environment.

7. Produce the capability to specify and forecast the intensity and location of plasma irregularities in the 100 km to 1000 km altitude region.

- Quantify the mechanisms for producing seed gradients in ionospheric density at high latitudes.
  e-field and density measurements along horizontal paths down to meter scale sizes
  ground based measurements of density velocity and neutral winds through the cusp.

- Discover the growth and damping mechanisms for high latitude structure.
  e-field and density measurements along horizontal paths down to meter scale sizes
- Specify the trigger mechanisms for structure formation at low and middle latitude during a solar cycle.
  Neutral atmosphere and wave environment.
  Lightning signatures
  Deep convection areas in the troposphere
- Predict the ionospheric and thermospheric conditions for maximum irregularity growth.
  F-region winds and ion drifts

Summary of LWS SAT discussions of required Observations/Instruments **for the magnetosphere, ionosphere, and thermosphere**

R. M. Robinson

7 February 2001

On Friday afternoon of the LWS SAT meeting, a subset of the SAT along with other attendees from NASA HQ, Goddard, APL and several other institutions met to identify observational requirements in the magnetosphere, ionosphere, and thermosphere (MIT) necessary to meet LWS strategic priorities as identified by George Withbroe. These areas of study are:

- Solar influences on climate
- Solar particle events
- Geomagnetic storms
- Nowcasting of the space environment
- Predicting the space environment
- Climatology of the space environment

In discussing the observations needed in the MIT, we established some ground-rules. First, detailed information about required observations would not be discussed. That is, the group felt the necessary expertise and time were not available to discuss specifics such as instrumentation, energy ranges, spatial, temporal, spectral resolution, etc. Second, we assumed that the necessary observations of the sun and solar wind upstream of the MIT system would be addressed in the solar and heliospheric groups. Third, in addition to observations, we felt it necessary to list models that were required so that observational input to the models would also be included. Finally, for each of the study areas listed above, we agreed upon a specific objective to be accomplished in making the observations and developing the models.

In the case of the first three, the specific objective is *to make observations that will allow researchers to track the effects of the designated phenomenon (global change, solar particle events, and geomagnetic storms) through the MIT system*. Specific scientific problems, or gaps in understanding, were not discussed. Rather, we proceeded on the premise that the availability of a full complement of instrumentation to observe the effects of these phenomena through the MIT system would provide the necessary information for scientists to address high-priority scientific problems.

In the case of the second group of three items listed above, the objective was *to identify the observations necessary to perform the stated task (nowcasting, predicting, and climatology)*. Here the observations we considered were strongly linked to models that would perform the stated tasks.

The results of the discussions are shown in the two attached tables. The format of the first table is a little different than the one used during our discussions. The format has been modified to make it more consistent with that used by the solar and heliospheric groups, where the first column contains a list of observables, and marks within the individual cells indicate whether the observation is required, as denoted in the legend. The rows in the table have been color coded. One color indicates observations that comprise the magnetospheric portion of the mission. Another color represents ionosphere/thermosphere observations. The third color represents models, where we have specified only broad categories of models that might be applied to each of the objectives.

After identifying the required observations, the group made a first attempt at defining spacecraft orbits that would be desirable in making the observations. Of course, without detailed costing, we could not anticipate the number of spacecraft that would be possible, but we were still able to identify preferred orbits and to discuss some of the trade-offs that might be made if the number of spacecraft proves to be a serious limitation. The second of the attached tables shows the type of spacecraft orbits desired and what broad types of measurements would be made on each platform. The first row shows the desired magnetospheric and radiation belt observations. The remaining rows show the ionospheric and thermospheric observations separated according to the space weather applications they address: scintillations, atmospheric drag, currents, and plasma structure. Note that the individual cells on the spreadsheet do not necessarily imply separate spacecraft; instrumentation addressing different objectives may be combined on a single spacecraft provided the required orbits are not conflicting.

Although it appears that the observations and spacecraft identified by the group are very similar to those selected in the notional missions (ionospheric and radiation belt mappers), there are some important differences. The spacecraft in highly elliptical orbits in the equatorial plane are not just dedicated to studying the radiation belts. They include, for example, instrumentation and energy coverage necessary to observe the cold plasma of the magnetosphere, along with the magnetospheric magnetic and electric fields. Similarly, the auroral imaging performed by instruments on the spacecraft in an elliptical polar orbit provides both magnetospheric and ionospheric observations. The polar orbiting satellites in low-earth orbit would make both ionospheric measurements and measurements of high energy precipitating particles to infer radial gradients in radiation belt fluxes. Finally, the instruments at geosynchronous orbit, whether or not they are made part of the SDO suite of instruments, could provide valuable in situ and unique remote sensing data for the entire MIT system. Thus, though these spacecraft resemble the notional missions, a clear delineation into two segments referred to as ionospheric mappers and radiation belt mappers is no longer appropriate.

Group 3 - Table 1. -- Required Observations

	Solar Influences on Global Change	Solar Particle Events	Geo-magnetic Storms	Now-casting	Space Environment Prediction	Space Environment Climatology
Energetic particles	X	X	X	X	X	X
Plasma			X	X	X	X
Magnetic fields		X	X	X	X	X
Electric fields			X	*	?	?
Waves			X	*	?	?
Electron density			X	X	X	X
Irregularities			X	*	X	
Scintillation			X	X	X	X
Convection	X		X	*	X	
AC electric fields and waves				*	X	
Particle precipitation			X	*	X	
Field-aligned currents			X	*	X	
Neutral density	X		X	X	X	X
Neutral winds	*		X	*	X	X
Neutral temperatures	X		X	*	X	X
Neutral composition	*		X	*	X	X
Mass outflow			X	*	X	
Auroral emissions	X		X	*	X	
GCM	X					
Middle atmos. chem. and dynamics	*					
Vertical coupling	*					
Particle precipitation	?					
Convection	?		X		X	*
Magnetosphere	?	X	X		X	X
Thermosphere-Ionosphere	*		X		X	
Radiation belt	?		X		X	*
Conductivity			X		X	
Data assimilation			X	X		X
Empirical models		X	X	?		X

Group 3 - Table 2. -- Required Spacecraft Orbits

Magneto-spheric and radiation belt observations

Equatorial LEO	Polar LEO	Polar Elliptical	Equatorial Elliptical	Geosynch-ronous	Equatorial L=2-4
	Measure-ment of precipitating energetic particle fluxes for human radi-ation exposure and role in global climate and global elec-tric circuit changes.	Remote sensing of magneto-spheric structure and dynamics from ENA, FUV, etc.	Magneto-spheric and radiation belt observations to extend to L-values of 8 to 10. Measure-ments to include energetic particles, cold plasma, electric and magnetic fields and waves. As many spacecraft as possible dis-tributed to obtain best local time coverage	For continuous monitoring of short time scale changes in the radiation and spacecraft charg-ing environ-ments without the time aliasing of el-liptical orbits.	For continuous monitoring of energetic parti-cles in the slot region which are transported and accelerated to very high energies in several minutes by shocks prop-agating through the magneto-sphere (e. g., the March 1991 event).

Scintillations

Equatorial LEO	Polar LEO	Polar Elliptical	Equatorial Elliptical	Geosynch-ronous	Equatorial L=2-4
Measure-ments of electron densities, ionospheric irregularities and scintilla-tions, electric fields and waves, and neutral winds, including a beacon, UV and 6300 imagers, GPS receiver, and possibly a topside sounder. At least one satellite, but as many as possible	Measure-ments of electron densities, ionospheric irregularities and scintilla-tions, electric fields and waves, and neutral winds, including a beacon, UV and 6300 imagers, GPS receiver, and possibly a topside sounder. At least one satellite, but as many as possible			Imaging for neutral and ionospheric densities and auroral emissions.	

Atmospheric Drag

Equatorial LEO	Polar LEO	Polar Elliptical	Equatorial Elliptical	Geosynch-ronous	Equatorial L=2-4
	In situ mea-surements of neutral density, composition, temperature, and winds. As many satellites as possible for maximum local time coverage, and lowest altitudes possible for neutral den-sities.			Imager for neutral com-position and density.	

Currents

Equatorial LEO	Polar LEO	Polar Elliptical	Equatorial Elliptical	Geosynch-ronous	Equatorial L=2-4
	Measurements of electric fields, magnetic fields, and auroral electron and proton pre-cipitation. As many satellites as possible for maximum local time coverage	Multi-spectral auroral imaging.		Multi-spectral auroral imaging.	

Plasma Structure

Equatorial LEO	Polar LEO	Polar Elliptical	Equatorial Elliptical	Geosynch-ronous	Equatorial L=2-4
In situ electron density measurements, topside sounder, limb scanning electron density measurements for altitude profiles, neutral winds and electric fields. As many space-craft as possible for maximum local time coverage. Optimize al-titude for most effective in situ and limb scanning measurement	In situ electron density measurements, topside sounder, limb scanning electron density measurements for altitude profiles, neutral winds and electric fields. As many space-craft as possible for maximum local time coverage. Optimize al-titude for most effective in situ and limb scanning measurement	Multi-spectral auroral imaging.		Multi-spectral auroral imaging.	

Report on LWS Workshop 31st January 2001: Global Change

Judith Lean
15 February 2001

The following scientists attended the SAT workshop on 31st January 2001 to provide inputs about solar influences on global change, including climate and ozone to the LWS program:

Mark Baldwin, Bob Cahalan, Charles Jackman, Gerry North, David Rind, Dave Rusch, Mike Schlesinger.

All had attended the successful LWS Sun-climate Workshop held in Tucson in March 2000, and agreed that the report of that workshop (available at http://www.ispe.arizona.edu/research/sunclimate/) provides a comprehensive assessment of the key questions and future research within three primary areas:
1) Direct solar forcing of climate variability and change
2) Indirect solar forcing of climate variability and change
3) The influence of energetic particles and coupling between upper and lower atmosphere on climate variability and change.

David Rind lead a discussion at the LWS Workshop to identify specific research likely to yield measurable advances within the 10-year nominal LWS program time-frame. A high priority for LWS research to understand the Sun's influence on global change are the following key questions:

What are the potential fingerprints of solar forcing of climate (spatial, temporal, altitudinal) and how do they compare with those due to other climate forcings and natural variability?

The approach to answer this question is as follows:
- Observe total, spectrally discriminated electromagnetic and energetic particle radiation variations
- Use models and observations to identify patterns of response to solar variations of different wavelengths and energy inputs
- Improve historical estimates of total and spectral irradiance variations (UV, visible, near-IR) during the last 2000 years
- Examine paleo and current data for solar-induced variations
- Compare model responses in ozone and planetary wave propagation to solar UV forcing with relevant observations
- Compare model response to GCRs, EEPs and SPEs to observations such as cloud cover
- Distinguish modeled and observed climate responses to solar forcing with that associated with trace gas increases, volcanic and tropospheric

aerosols, and natural (atmosphere-ocean) variability in four dimensions (x,y,z,t)

- Encourage development of solar models capable of hindcasting and predicting solar activity and energetic output variations.
- Calculate potential climate response to estimated future solar irradiance variations, and compare the magnitude and pattern of response to that estimated for future anthropogenic forcing and natural variability

The group noted the following:

The Sun-Climate Problem:
Understanding Sun-climate relationships is a very hard problem. Pursuit of this understanding has been undertaken, with varying levels of acceptance by the broader climate community, for more than a century. The problem of specifying the relationships and their mechanisms has yet to be “solved”. Needed are very good statistical tools, very good datasets, and a commitment to research the problem.

The Sun-Climate Opportunity:
The solar irradiance cycle is one of the few known external forcings of the climate system. Its variations have been well documented during the past two solar cycles, at the same time that extensive climate records have been acquired. A real Sun-climate connection, once established, would provide a unique and stringent test of climate models on decadal time scales. This is because Sun-climate mechanisms likely involve multiple climate processes and feedbacks, both linear and non-linear, direct and indirect. They involve vertically differentiated radiation, chemistry and dynamics, responding simultaneously to changes in solar electromagnetic radiation in different wavelength bands and possibly energetic and galactic particles, incorporating vertical atmospheric coupling, and internal atmosphere-ocean oscillations.

Weather and Climate:
Research into solar effects on weather (as opposed to climate) has not been fruitful in the past because of dubious claims based on empirical relations with large statistical certainties, and the lack of plausible mechanisms. Nevertheless, the possibility of such short time-scale relationships should not be dismissed since the effects may be subtle. Advances in identifying a solar role in weather, if such a connection exists, would be of more immediate societal relevance than sun-climate. This is because weather has a more direct effect on society, and is generally more positively perceived than is climate change, which is considered a “threat”. Thus LWS should encourage research on all time scales – from weeks to ice ages.

Office of Earth Science Programs:
The primary observational and modeling infrastructure needed to accomplishing research in solar influences on global change already exists to a large extent within the Office of Earth Science climate and middle atmosphere communities (http://eospso.gsfc.nasa.gov/). The planned EOS measurements, analysis and modeling are being undertaken primarily for purposes other than Sun-climate research, but LWS can utilize, and need not duplicate, OES tools and datasets. Of crucial importance for LWS in the OES program to monitor the total solar irradiance and the spectrum from 120 nm to 2000 micron that the SORCE spacecraft will make, commencing in 2002, with the specific goal of defining solar radiative climate forcing. This solar monitoring is planned to continue on EOS-4, and provide eventual overlap with NPOESS, for which solar irradiance monitoring (total and spectral from 0.2 to 200 micron) is an operational EDR.

Ozone and Global Change:
Although climate change may be the highest priority of global change research, specifying and understanding changes in ozone concentration are important in their own right. This is because of the societal and biological effects of increased UV radiation cause by ozone depletion, which the Montreal Protocol was put in place to mitigate. To properly specify the Sun's influence on ozone requires additional measurements and models, typically at higher altitudes, than are needed for understanding climate change alone. Some important measurements, especially odd nitrogen compounds such as NO, are not being made at all, or over the required altitude range. LWS should assess whether it needs to undertake additional observations that are likely crucial for understanding solar influences on ozone, or whether these measurements are being made by non-US missions.

Sun-Climate Community:
Researchers working in this field are small in number and typically undertake Sun-climate research as a "sideline" activity. It is highly unlikely that the research needed to specify and understand the Sun's influence on global change will be attended to elsewhere (than within LWS), and it will not be seriously undertaken unless specific funds are allocated for this task. A great amount of data that could be directed to this problem already exist –a focused data mining effort will likely be fruitful. Many other efforts are focusing on global change related to non-solar influences and it is important that funds not be diverted to these efforts at the expense of focused Sun-climate tasks.

Appendix 1 -- List of scientific community invitees to workshop

Name		Affiliation	Expertise
Mark	Baldwin	Northwest RA	climate
Bern	Blake	Aerospace	magnetosphere
Bob	Cahalan	GSFC	climate
Bob	Clauer	U Michigan	ionosphere
Odile	de la Beaujardiere	AFRL	ionosphere
Michael	Dettinger	USGS / SCRIPS	climate
George	Fisher	UCB	solar
John	Foster	MIT Haystack	ionosphere
Tim	Fuller-Rowell	NOAA/CIRES	Ionosphere
Shing	Fung	GSFC	magnetosphere
Alan	Gary	MSFC	solar
Peter	Gilman	HAO	solar
Chuck	Goodrich	U Md	interplanetary
Jack	Gosling	LANL	interplanetary
Dave	Hathaway	NASA/MSFC	solar
Mary	Hudson	Dartmouth	magnetosphere
Stuart	Huston	Boeing	magnetosphere
Charlie	Jackman	GSFC	climate
Steve	Kahler	AFRL	interplanetary
Steve	Keil	NSO	solar
Lynn	Kistler	U New Hampshire	interplanetary
Janet	Kozyra	U Michigan	mangetosphere
John	Leibacher	NSO	solar
Xinlin	Li	U Colo	magnetosphere
Dana	Longcope	Montana State	solar
Frank	Marcos	AFRL	atmosphere
John	Mariska	NRL	solar
Sara	Martin		solar
Dave	McComas	SwRI	interplanetary
Robert	McCoy	ONR	ionosphere
Zoran	Mikic	UCSD	interplanetary
Gerald	North	Texas A&M	climate
Terry	Onsager	NOAA/SEC	magnetosphere
Michael	Picone	NRL	atmosphere
David	Rind	NASA GISS	climate
David	Rusch	U Colo	climate
Michael	Schlesinger	U Illinois	climate
Jesper	Schou	Stanford	solar
Neil	Sheeley	NRL	interplanetary
George	Siscoe	Boston U	magnetosphere
Jan	Sojka	Utah State	ionosphere

Robert	Strangeway	UCLA	magnetosphere
Keith	Strong	Lockheed	solar
Ted	Tarbell	Lockheed	solar
Brian	Tinsley	UT Dallas	ionosphere
Larry	Townsend	U of Tenn	atmosphere
Aad	van Ballegooijen	SAO	solar
Tom	Woods	U Colo	solar
Ron	Zwickl	NOAA/SEC	interplanetary

Appendix 2 -- List of registrants at workshop

Brian	Anderson	JHU / APL
Spiro	Antiochos	NRL
Mark	Baldwin	Northwest Research
Janet	Barth	NASA/ Goddard Space Flight Center
Sanitmay	Basu	AFRL
Sunanda	Basu	AFRL
Bern	Blake	Aerospace
Robert	Cahalan	NASA/ Goddard Space Flight Center
Mike	Calabrese	GSFC
Bob	Clauer	University of Michigan
Gil	Colon	GSFC
Tony	Comberiate	GSFC
Odile	de la Beaujardiere	AFRL
George	Fisher	University of California
Len	Fisk	University of Michigan
John	Foster	MIT
Nicola	Fox	JHU / APL
Tim	Fuller-Rowell	NOAA
Shing	Fung	NASA/ Goddard Space Flight Center
Alan	Gary	NASA/ Marshall Space Flight
Barbara	Giles	GSFC
Peter	Gilman	University of Colorado
Greg	Ginet	AFRL
Charles	Goodrich	UMD
Jack	Gosling	LANL
David	Hathaway	NASA/ Marshall Space Flight
Gary	Heckman	NOAA
Rod	Heelis	University of Texas
Fred	Herrero	GSFC
Michael	Hesse	GSFC
Todd	Hoeksema	NASA HQ
Joanie	Hoffman	NASA/ Goddard Space Flight Center
Robert	Hoffman	GSFC
Mary	Hudson	Dartmouth University
Stuart	Huston	Boeing
Charles	Jackman	NASA/ Goddard Space Flight Center
Mike	Jamilkowski	OSD / C31
Steve	Kahler	AFRL
Steve	Keil	NSO
Paul	Kintner	Cornell University
Lynn	Kistler	University of New
Marsha	Korose	OSD / C31
Terry	Kucera	GSFC

Guan	Le	GSFC
Judith	Lean	NRL
John	Leibacher	National Solar
Xinlin	Li	Colorado University
Dana	Longcope	Montana State
Laura	Madachy	Westover Consultants
Frank	Marcos	AFRL
John	Mariska	NRL
Sara	Martin	Helio Research
Glenn	Mason	UMD
Barry	Mauk	JHU / APL
Dave	McComas	SWRI
Robert	McCoy	ONR
Mary	Mellott	NASA HQ
Dick	Mewaldt	Caltech
Zoran	Mikic	UCSD
Gerald	North	Texas A&M
Arlene	Peterson	GSFC
Rob	Pfaff	GSFC
Michael	Picone	NRL
Vic	Pizzo	NOAA
Art	Poland	NASA/ Goddard Space Flight Center
Kenneth	Potocki	JHU / APL
Shannon	Powell	Westover Consultants, Inc.
Geoff	Reeves	Los Alamos National
David	Rind	GISS
Bob	Robinson	NSF
John	Robinson	GSFC
Dave	Rusch	University of Colorado
David	Rust	JHU / APL
Mike	Schlesinger	University of Illinois
Jesper	Schou	Stanford University
Karel	Schrijver	Lockheed Martin
Neil	Sheeley	NRL
David	Sibeck	JHU / APL
Howard	Singer	NOAA
George	Siscoe	Boston University
Jan	Sojka	Utah State University
Robert	Strangeway	UCLA
Keith	Strong	Lockheed Martin
Ted	Tarbell	Lockheed Martin
Barbara	Thompson	NASA/ Goddard Space Flight Center
Brian	Tinsley	University of Texas
Larry	Townsend	University of Tennesee
Aad	van Ballegouijen	SAO
Guoyong	Wen	UMBC/GSFC

George	Withbroe	NASA
Dick	Wolf	Rice University
Donald	Woods	LASP
John	Wygant	University of Minnesota
Sam	Yee	JHU / APL
Larry	Zanetti	JHU / APL
Ron	Zwickl	NOAA